Reciprocating Ball Screw Generator (ReBaS)

WES Power Take Off
Stage 2 Project
Public Report

Umbra Cuscinetti S.p.A.

This project has been supported by Wave Energy Scotland

1 Project Report

1.1 Project Introduction

This document provides a summary of the “ReBaS (Recirculating Ball Screw) generator” project, commissioned by Wave Energy Scotland (WES) under a stage 2 contract as part of the call for Wave Energy Converters (WECs) Power Take-Off (PTO) systems.

The project embraced a series of activities to facilitate the technology transfer of a well-proven, highly efficient Electro-Mechanical Actuator (EMA) derived from the aeronautic and industrial sectors, and developing this concept as a generic PTO option for wave energy applications (see Figure 1). The ballscrew generator inverts the basic operation of an EMA and integrates two systems: a reciprocating ballscrew, which converts linear motion into rotary motion, and a permanent magnet generator, which converts rotary motion into electricity.

Figure 1: The ballscrew generator produced by Umbra Cuscinetti.

The project was undertaken by a consortium led by Umbra Cuscinetti from Italy, a world leader in the production of recirculating ballscrews and electromechanical systems for the aeronautical, energy and industrial sectors. Project partners included Hebrides Marine Services (HMS) Ltd, a spin out company of the University of the Highlands and Islands based in the Outer Hebrides of Scotland and SeaPower scrl, an Italian consortium company based at the University of Naples “Federico II”. HMS performed project management activities, while SeaPower scrl coordinated the fabrication of a point-pivoted buoy, used to test the generator in a wave tank.

The project has proven the performance and robustness of the ballscrew generator. Indeed, it was able to work with efficiencies between 70% and 80% for a wide range of operating conditions (both dry and wet) and to successfully pass a HALT (Highly Accelerated Life Testing) endurance test of 2,000,000 cycles.

1.2 Description of Project Technology

A screw is a load-carrying mechanical component able to convert linear motion into rotary motion and vice versa. This concept is easy to understand if we think of the screws we use at home. A ballscrew, as simply shown in Figure 2, is a mechanical device in which the “balls”, acting as low friction load-carriers, convert the linear motion of the “screw” into rotary motion of the “nut”. Thanks to the balls, the axial load at the screw is converted into a torque at the nut, which is free to rotate about the axis of the screw but axially constrained. The rotational speed of the nut is a function of the screw linear speed and the screw pitch (i.e. the axial distance between adjacent threads on the screw).

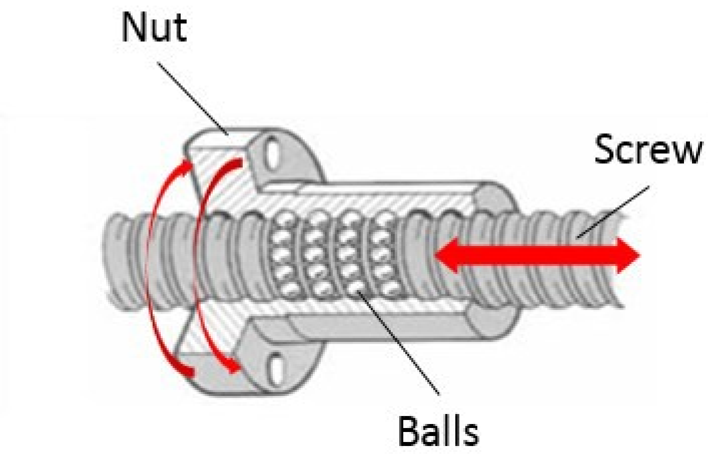

Figure 2: Schematic representation of a ballscrew system.

Permanent magnets are integrated in the nut, which acts thus as rotor of the electrical generator. The rotor spinning inside a specially designed stator produces electrical output energy thanks to the principle of electromagnetic induction. The frequency of the induced voltage and current on the stator windings is proportional to the input speed and generator number of poles. The screw pitch and number of the generator poles are thus adjustable parameters that can be tuned to match the requirements of a specific application.

Umbra Cuscinetti's ballscrew technology has been successfully adopted in various sectors including aerospace, industrial, military, nuclear and medical. Compared to the presently most popular PTO choices for wave energy (namely hydraulic, other direct drive and pneumatic), this system has several clear advantages including:

- **Efficiency**: mechanical power is directly converted to electrical power, without the need of an intermediate conversion step. Mechanical efficiency is high due to the small friction inherent within the system (only rolling contact elements are used). The rotary motion amplifies the variation of the magnetic field leading to a higher electrical efficiency.
- **Reliability**: the short energy conversion chain and the reduced number of components increases the system overall reliability, minimizing mean time between failures (MTBF) and downtime for maintenance and parts replacements.
- **Survivability**: the ballscrew technology has the ability to withstand high fatigue cyclic loading. The high efficiency delivered for a wide range of loads allows the generator to well perform in applications with high load ratios or low capacity factors.
- **Applicability**: thanks to the linear reciprocating motion between input shaft and housing, the application of a ballscrew generator to WEC types such as point absorbers and submerged pressure differential is straightforward. An easy adaption of the ballscrew generator to WECs where a rotating motion occurs (such as oscillating wave surge converters and attenuators) can be implemented by placing the generator inside a pin-to-pin connection between the moving parts.

- **Costs**: the overall short energy conversion chain (with consequent reduction of the number of components used) and the use of few costly active materials for the electric generator (such as magnets, copper and ferromagnetic) result in competitive costs for the PTO.

- **Manufacturability**: the system has a relatively simple architecture, with a reduced number of components. The derivation from an already industrialized device allows for a lean and optimized production cycle, that is already available. Production and assembly costs are consequently within competitive known boundaries.

- **Power density:** all the components needed for mechanical to electrical energy conversion are integrated inside a compact envelope, with a relatively small weight. This reduces the impact of PTO installation on a WEC both in terms of weight and space requirements.

1.3 Scope of Work

The work undertaken in this project consisted in a detailed characterization of the generator performance under different operating conditions. In particular, the following activities took place:

- Dry tests at Umbra Cuscinetti's test bench, to assess the performance of the generator for different damping factors and input conditions.

- Endurance test at Umbra Cuscinetti's test bench, to measure the ability of the device to survive persistent, cyclic loads.

- Wet tests at the wave tank of the University of Naples "Federico II", where the generator was connected to a specifically designed point-pivoted buoy, to assess its performance under scaled realistic operating conditions.

- Numerical simulation, to understand, assess and predict the generator performance in both wave tank tests and future developments.

During the dry tests, the ballscrew generator was axially connected to an electro-mechanical actuator (EMA). The EMA was controlled so that a specific axial position profile (trapezoidal, sinusoidal or irregular) could be imposed to the ballscrew generator input shaft, which was connected to a purely resistive electrical load. Figure 3 and Figure 4 shows a picture and the layout of the dry test setup used in this project. The aim of this activity was to assess the generator performance for a wide range of operating conditions in terms of screw axial speed and electrical load resistance.

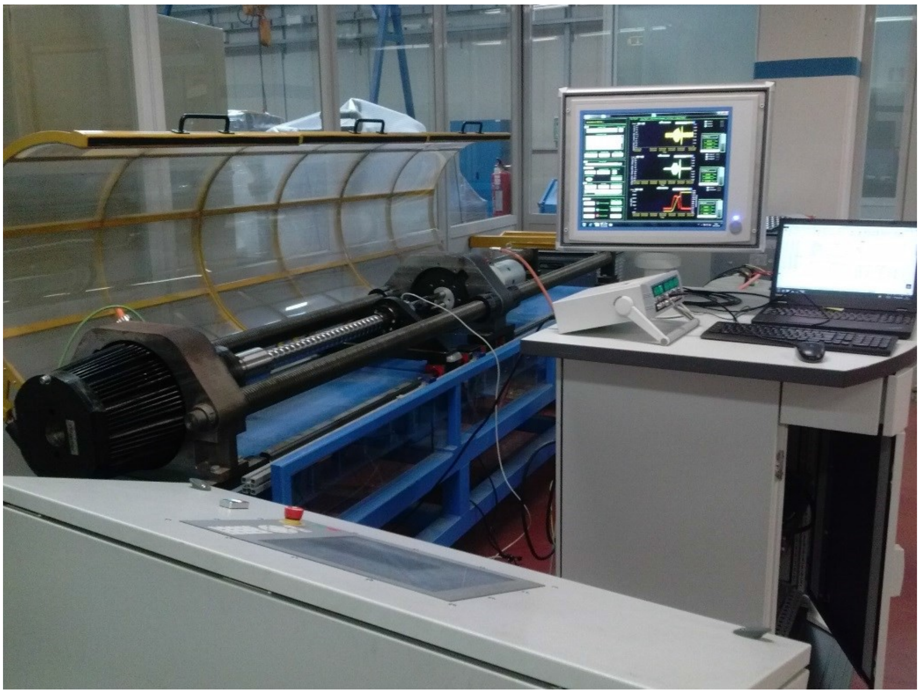

Figure 3: Picture of the dry test rig used at Umbra Cuscinetti.

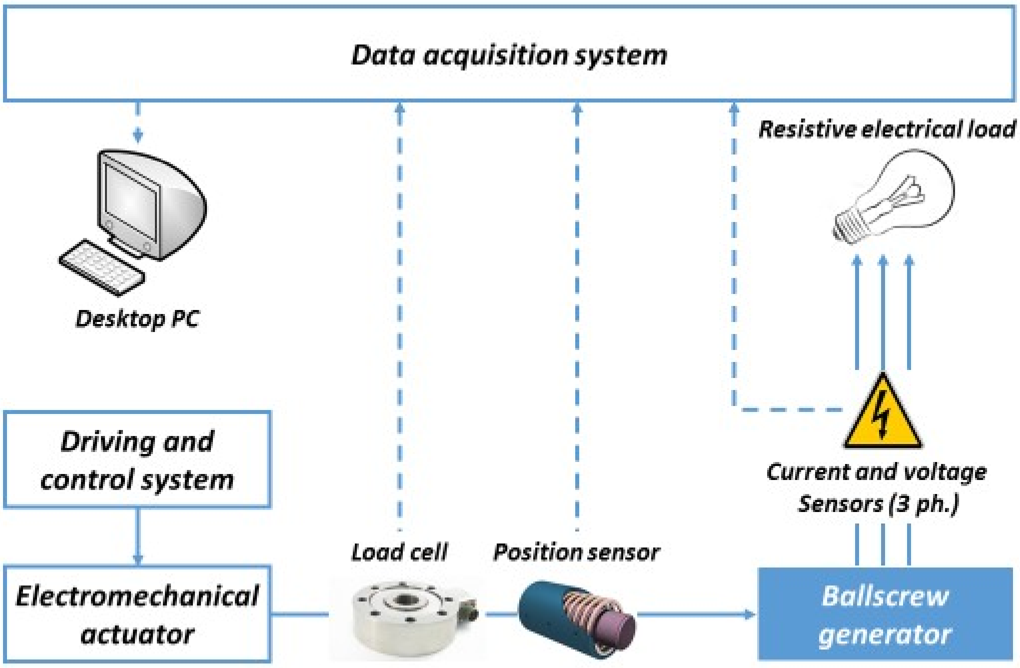

Figure 4: Layout of the dry test rig used at Umbra Cuscinetti.

Besides performance tests, the generator has undergone an endurance dry testing programme at the Umbra Cuscinetti production and test facility in Foligno. In total, the generator completed 2,000,000 cycles at maximum force (35kN) and speed (950 mm/s).

The consortium performed also wet tests where the generator was connected to a point-pivoted buoy (see Figure 5). The buoy shape and configuration is the result of previous intense numerical and experimental studies, aimed at maximizing the system hydrodynamic efficiency. The generator was placed between the buoy and a support structure on the wave tank carriage. The connection was performed through two mechanical hinges. As in the dry test, a resistive electrical load bench was used. Tests were performed with both regular waves (heights up to 50 cm) and irregular waves (Pierson-Moskowitz and JONSWAP spectra with significant wave heights of up to 25 cm).

Figure 5: The ballscrew generator and the point-pivoted buoy during wet tests.

1.4 Project Achievements

The main project achievement has been the experimental demonstration of ballscrew generator performance. Figure 6 shows the efficiency as a function of the input force and screw axial speed, where efficiency is defined as the ratio between the mean electrical power available at the generator terminals and the mean mechanical energy at the input screw shaft. Results are shown for constant speed dry tests. Figure 6 highlights three important results obtained during this project:

- **The efficiency is high**, and values up to 87% are observable.
- **The efficiency is stable over a wide range of speeds**, and has only a small drop at very low speeds.
- **The efficiency is nearly independent of the input conditions**, and mainly affected by screw shaft speed.

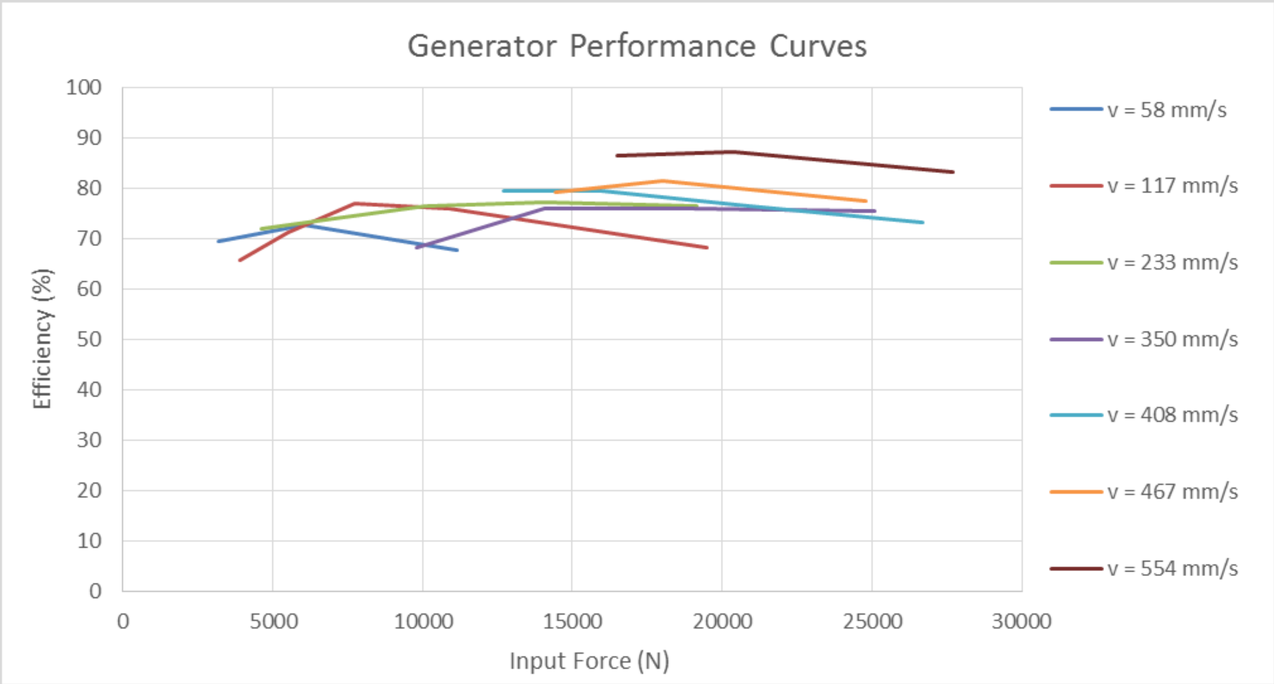

Figure 6: Efficiency of the ballscrew generator for constant speed dry tests

It is worth mentioning these results were confirmed by all the other tests (both dry and wet), with very narrow efficiency variations for different input conditions.

The endurance test was also very successful. Assessments and inspections were carried out after 600,000 cycles and at the end of the test programme on several components of the generator, including screw, balls and nuts. All the components remained in excellent conditions, with no visible evidence of fatigue damage, wear and malfunctioning. This outstanding result confirms past achievements obtained by Umbra Cuscinetti with similar machines manufactured for the industrial and aeronautic sectors.

Another important achievement generated by the project has been the opportunity to actively raise awareness of the technology to other wave energy developers for the purposes of exploring future opportunities for integration with more established technologies. The project has functioned as a platform for discussion with other technology developers and as a result, negotiations to establish formal partnerships are ongoing.

1.5 Applicability to WEC Device Types

The “ReBaS” system has the potential to integrate with many WECs using linear displacement in the PTO, including classical concepts as (see Figure 7):

- Attenuators;
- Point absorbers;
- Oscillating wave surge converters;
- Submerged pressure differential concepts.

Integration can be achieved via selection of appropriate stroke and control law for these concepts, thus requiring only minor adjustments/modifications to original designs. In addition, the “ReBaS” generator is applicable to any other concept where a transformation from linear to rotational motion is required: by using a lever, the high torque – low rotational speed motion can be transformed in a reduced force – increased speed motion. In this way, the lever works as a first-stage gearbox and its length can be optimized with respect to the working conditions and space requirements. Moving the input mechanical power on lower loads and higher speeds can also solve problems of peak loading (typical of wave energy applications) and allows the generator to work in the higher efficiency area.

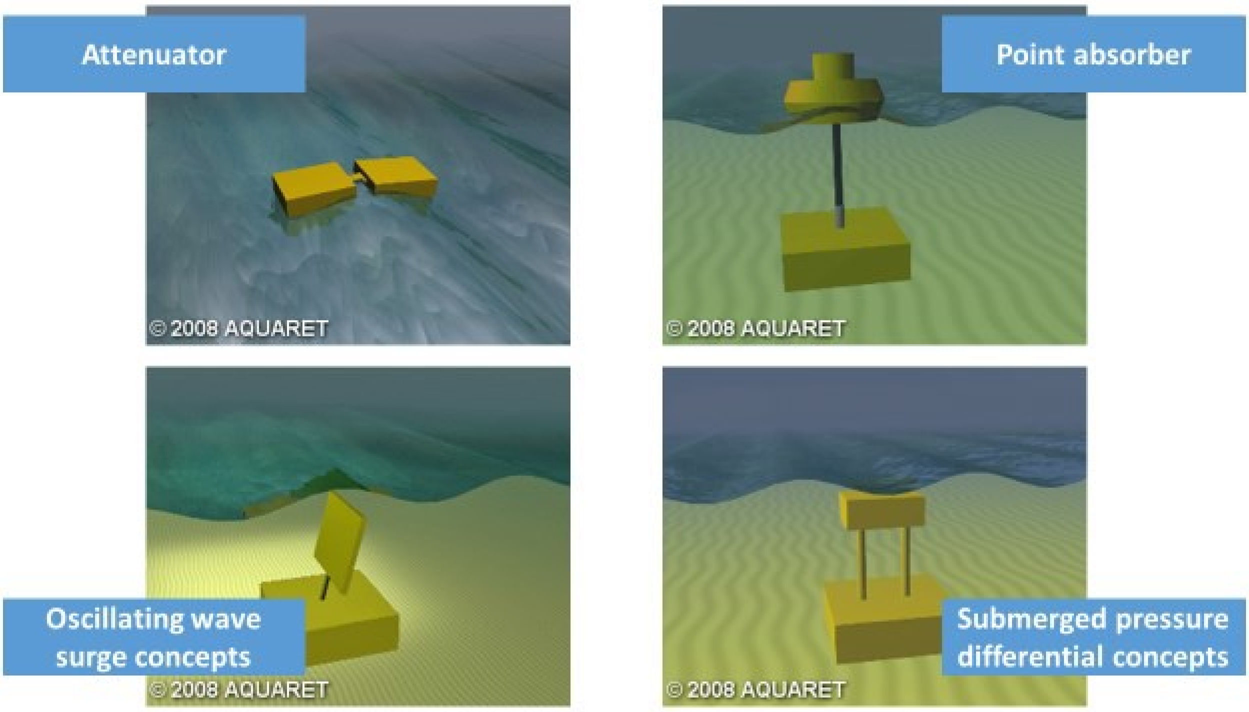

Figure 7: Wave energy conversion concepts that could directly integrate the "ReBaS" generator.

Most of the concepts mentioned are currently using hydraulic PTOs, a popular choice since they well match the requirements of low speed and high force applications, with the additional benefit of component availability and track records from various fields including heavy duty and marine applications.

However, the "ReBaS" generator has a number of specific advantages over hydraulic systems: their efficiency tends to be poor due to the inherent requirements for several energy conversion steps and the efficiencies associated with multiple separate components required in each system (see Figure 8). Hydraulic systems have extensive equipment and component requirements, can be prone to leakages, are typically bulky and have high inherent operation and maintenance costs due to the contamination sensitive nature of the system and requirement for oil changes.

In addition, the "ReBaS" generator is also very competitive compared to purely linear electrical generators. Indeed, the ballscrew technology has a higher economical potential due to the lower usage of active materials such as magnets, copper and ferromagnetic materials, and a higher technological flexibility given by the adjustability of design parameters such as the screw pitch and the number of poles. The electro-mechanical architecture allows a high possibility of integration with many control strategies; thanks to the fully reversibility of this device an active control can be applied as well, letting the generator work as an EMA.

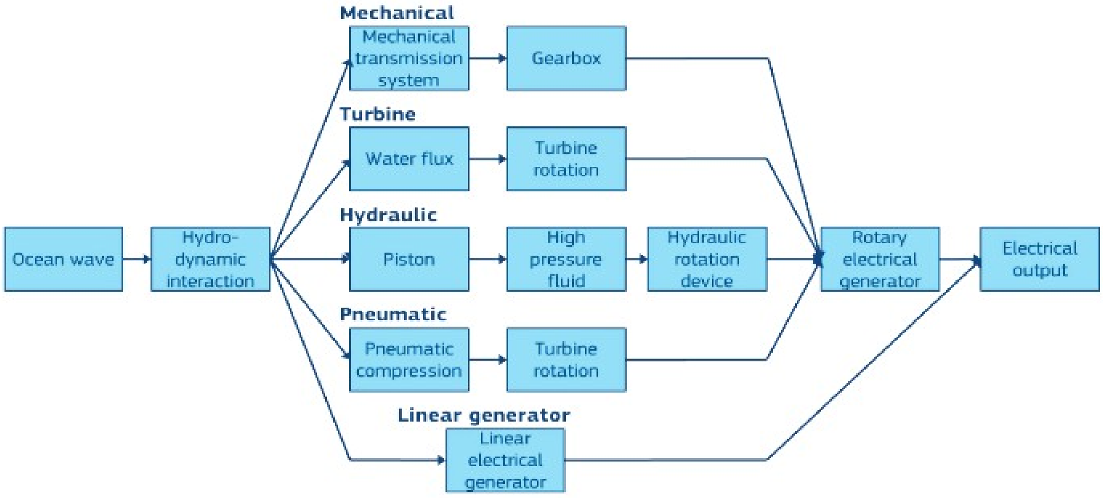

Figure 8. Comparison of PTO permutations for wave energy conversion[1].

1.6 Summary of Performance against Target Outcome Metrics

Project success was measured by a series of target outcomes (TOs) collated by the consortium prior to project inception. Target outcomes were defined based on affordability, performance, availability and survivability. Indications at both current project level and future industrial level are provided below for the "ReBaS" generator.

Affordability

In terms of manufacturability, the ballscrew generator has the potential for being a ground-breaking technology. Indeed, it is a derivation from the EMAs commercialized by Umbra for which a well-established production facility in Foligno (Italy) with a robust and developed supply chain already exists. Furthermore, similar machines with power ratings up to 300 kW have already been manufactured by Umbra at competitive costs. Estimates at the end of the project suggest that a cost of £525/kW is achievable for an industrialized 40-60 kW PTO. Non-linear scale effects are foreseen, bringing to a lower cost per kW for higher PTO sizes. The generator was easy and quick to install on a point-pivoted buoy, and confidence was gained in considering it easy to integrate with different devices.

Performance

At the beginning of the project, a maximum efficiency of 85% was declared; dry tests showed efficiencies up to 87%, which is above expectations. More important, the efficiency was stable between 70% and 80% for most of the tests (both dry and wet), independently of the operating conditions.

Availability

During this project, the "ReBaS" generator was tested under different operating conditions for more than 800 hours. No wear, damage or malfunctioning occurred at any point. This was expected by Umbra Cuscinetti S.p.A., which already designed EMAs for the aeronautic sectors which operated continuously for 20 years within the design conditions.

1 https://setis.ec.europa.eu/sites/default/files/reports/2014-JRC-Ocean-Energy-Status-Report.pdf

Survivability

The “ReBaS” generator experienced load ratios up to 3.69 referring to the ratio between maximum and average screw axial force experienced in the single test (either dry or wet). Nevertheless, considering the peak loads experienced continuously during fatigue dry test, the generator could have resisted load ratios between 7 and 15, depending on test conditions.

In terms of reliability and fatigue life, the generator was tested continuously at its maximum axial load, performing 2,000,000 cycles. Visual and dimensional checks after the test showed no sign of mechanical damage.

1.7 Communications and Publicity Activity

A number of activities were carried out to promote the project and the outputs:

Conferences and Papers

An abstract was submitted with accompanying paper and a poster was presented at the International Conference on Ocean Energy (ICOE), Edinburgh, February 2016: “An Innovative PTO for a Point Pivoted Absorber for Wave Energy Conversion”.

A paper was presented at the International Conference on Offshore Renewable Energy (CORE) in September 2016: “Performance of a Point Pivoted WEC Equipped with a Linear Ball Screw Generator in Regular Wave Conditions”.

A poster has been presented at the UHI Research Conference 2016 in Inverness and has been awarded price for ‘Best Poster’. “Device Testing: Large Scale Prototype Testing of an innovative Wave Energy Converter”.

A paper has been submitted and will be presented at the Asian Wave and Tidal Energy Conference (AWTEC), Singapore, October 2016: “Dry and Wet Testing of a PTO based on Recirculating Ballscrew Technology”.

Media and Press Releases

A promotional video was created showcasing tank tests and activities around the project.

1.8 Recommendations for Further Work

The “ReBaS” project has delivered excellent results and the ballscrew generator has reached a TRL 5. The next stage of testing to capitalise on project success and explore further opportunities for development is scaling up to a 60 kW PTO, test in a real sea environment to prove out the concept in an operational environment and begin to gather work for a commercial scale prototype. Specific activities in the short/mid-term include:

- Gain experience from wet tests on marinized generator (seals, bio-fouling prevention, corrosion protection);
- Progress of customer interactions to ensure engagement of the PTO simulation, engineering and integration with host device developers;
- Development of a preliminary O&M plan related to a certain WEC application;
- Development and implementation of safe systems of work within the marine environment and securing initial third party validation of specific aspects of the technology if necessary.